ON THE MOTION AND SENSATION OF SOUND *

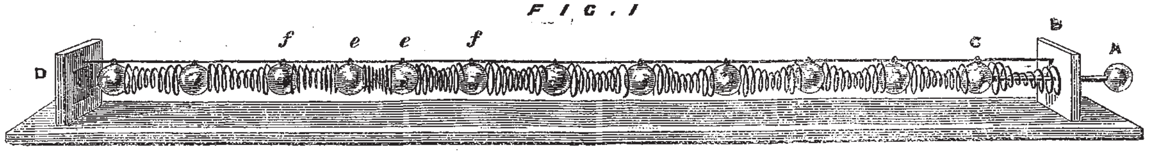
LECTURE I.

IT is needless for me to say to the ladies and gentlemen who honour these lectures with their presence, that they are intended more especially for the instruction of boys and girls. As in all other cases where it has fallen to my lot to teach others, I shall endeavour, while avoiding superficiality, to strip the subject of all unnecessary difficulty, and of all parade of learning, and to present it in simplicity and strength to the youthful mind.

The title of the lectures is, The Motion and Sensation of Sound. Now every boy knows what I mean when I speak of the sensation of sound. The impression, for example, of my voice at the present time upon the organ of hearing is the sensation of sound. But what right have I to speak of the motion of sound? This point must be made perfectly clear at the beginning.

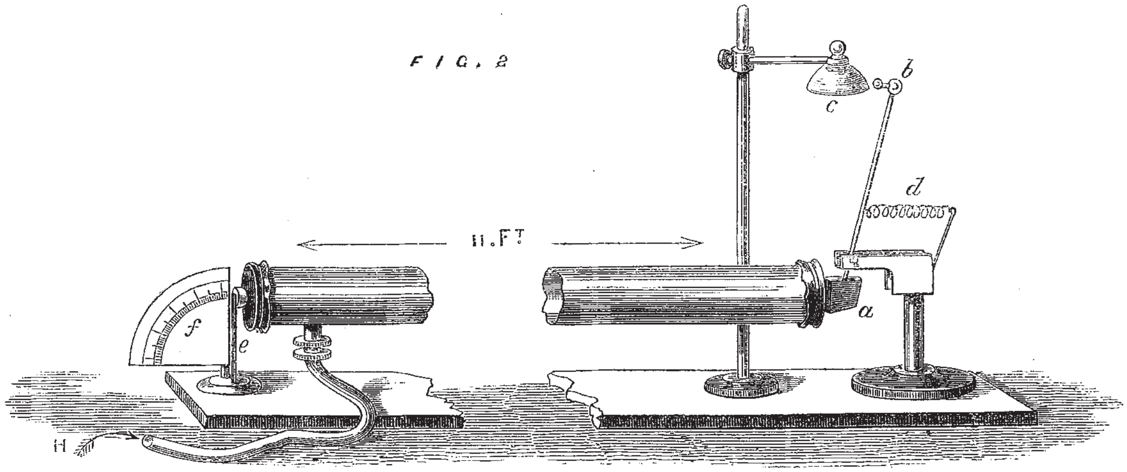
For this purpose I will choose from among you a representative boy, or allow you to choose him, if you prefer doing so. This boy, whom you may call Isaac Newton, or Michael Faraday, will go with me to Dover Castle, make the acquaintance of the general commanding there, Sir Alfred Horsford, and explain to him that we wish to solve an important scientific problem. He is sure to help us: he will lend us a gun, and an intelligent artilleryman; and we will make arrangements with this man to fire the gun at certain times during the day. We set our watches together; and now, before quitting him, we ask the artilleryman to fire one shot. We are close at hand, and we observe the flash and listen to the sound. There is no sensible interval between them. When we stand close to the gun flash and sound occur together.

FIG. 1



Well, we quit the artilleryman, warning him to fire at the exact times agreed upon. Let us say that the first shot is to be fired at 12 o'clock, the second at 12.30, and so on every half hour. We quit our artilleryman at half-past eleven, descend from the castle to the sea-shore, where a small steamer is awaiting us. We steam out a little better than a mile from the place where we have left the artilleryman; and now we pull out our watches and wait for 12 o'clock. Newton at length says, "In exactly half-a-minute the gun ought to fire;" and, sure enough, at the exact time agreed upon, we see the flash of the gun. But where is the sound which occurred with the flash when we were on shore? We wait a little, and precisely five seconds after we have seen the flash we hear the explosion; the sound having required this time to travel over a little better than a mile.

FIG. 2



We now steam out to twice this distance and wait for the 12.30 gun. We see the flash, but it requires ten seconds now for the sound to reach us; we treble the distance, it requires fifteen seconds; we quadruple the distance, and find the sound requires twenty seconds to reach us. And thus, if the day were clear, we might go quite across to the coast of France and hear the gun there. In all cases we should find that the flash appeared at the precise time agreed upon with the artilleryman, which proves that light reaches us in so short a time that our watches fail to give us any evidence that the light requires any time at all to pass through space, while the sound reaches us later and later the farther we go away. I think these experiments give us every right to speak of the "Motion of Sound."

But they also inform us how the velocity of sound has been actually determined. The most celebrated experiments on this subject have been made in France and Holland. Two stations were chosen ten or twelve miles apart; guns were fired at each station, and the interval between the flash and the report was accurately measured by the observers at the other station. In this way it was found that when the air is at the temperature of freezing water, the velocity of sound through it is 1,090 feet a second. On different days we should find it travelling at different speeds—as the weather grows warmer the sound is found to travel faster.

But I must not let you go with the idea that light requires no time at all to pass through space. This great problem has also been solved; and we now know that while sound moves at the rate of 1,090 ft. a second, light passes over the almost incredible distance of 186,000 miles in the same time. Hence at the distances employed in our observations, our watches were entirely unable to inform us that light required any time at all to pass through space.

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* Royal Institution Christmas Lectures, 1873—4, by Professor Tyndall, D.C.L., LL.D., F.R.S. These lectures have not been written out, much less intended for publication. At the request of our Reporter, Dr. Tyndall has consented to their appearance in NATURE.

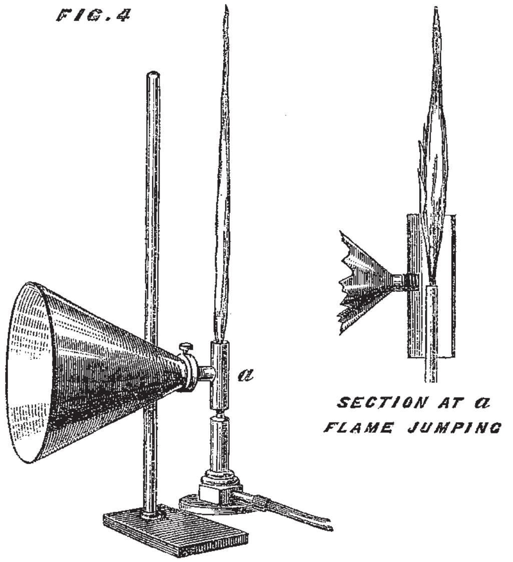
But if I stopped here, your next question would be—What is this thing which passes through the air with a velocity of 1,090 ft. a second, and which, when it reaches us, makes us hear an explosion? We must give a thorough and complete answer to this question, but to do this we need a little preparation. Like sailors going into battle, we must clear our decks for action; and here I must ask you to give me your patient and resolute attention.

In order to know how sound is propagated through the air, we must first know something regarding the air itself. Let us examine the air.

First, the air has weight. It presses upon a single square foot of this table with the weight of nearly a ton (144 × 15 = 2,160 lbs.). I have here a glass cylinder covered at the top with a sheet of india-rubber. The air presses on that surface with the weight of nearly 900 lbs. But then you will ask how the india-rubber bears it. Why is it not pressed in? Because air is on both sides of it, and the pressure on the inside is exactly equal to that on the outside. But if I take away the air from the inside of the cylinder, you will soon see the india-rubber pressed down by the weight of air above it.

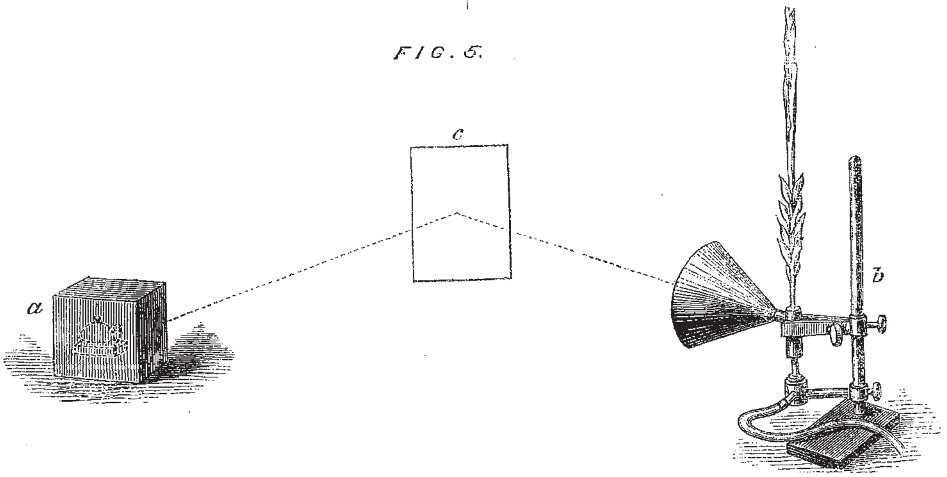
[A tube from an air-pump was then attached to a pipe communicating with the interior of the cylinder, which stood on a brass plate, to which its edges were ground parallel; the pump was set in action, and the india-rubber diaphragm at once sank down, in the end clinging to the sides of the glass, forming a deep vessel lining the inside of the cylinder.]

FIG. 4



SECTION AT *a*
FLAME JUMPING

FIG. 5.



When the air is let in again, you observe the rubber returns slowly to nearly its primitive position; it would entirely, but that the india-rubber is a little over-stretched.

We have thus seen the effect of removing the pressure from the inside. What would occur if we took the outside pressure away? The india-rubber would expand. Instead of trying to remove the whole of the air from this room, which is impossible, I will cover these two slack and collapsed bladders with this glass vessel, fitting accurately on to the plate, over which they are suspended; and then draw off by the air-pump the air surrounding them. See how they gradually blow out; the folds are now nearly abolished; now they have become quite smooth.

Why is this? Because the air particles have the power of pushing one another apart, and thus take up sufficient space to fill the bladders when the external pressure is removed. The air in this room is pressed upon by the weight of the whole atmosphere. The repelling force which the air particles exert upon each other is called the elastic force of the air.

Now we have to consider how the sound of the gun is propagated through air. Does the gun fire anything through the air? No. We may in a rough way represent the particles of air by the solitaire balls arranged in a row close together in this groove. I take the first one and roll it against the second. You observe the row does not move, only the end one goes away. The first delivers up its motion to the second, and then stops, the second delivers its motion to the third, the third to the fourth, and so on until the last, which, meeting no resistance, flies off. In this way we may figure the motion as transmitted from particle to particle of the air.

A still better idea may be derived from this model (Fig. 1), which has been devised by the ingenuity of my assistant, Mr. Cottrell.

In my hand I hold a stem (A), passing through the upright (B), by which a shock can be sent from a ball (C) through a spring to another ball, thence through another spring to another ball, and so on, until at last the shock reaches the last ball, which is projected against the india-rubber pad at the end (D), placed there to represent in a rude mechanical way the drum of the ear. I press the stem (A), with a sudden motion of my hand, and you see that though the ball (C) only moves to and fro, yet it sends forward a kind of pulse (*f e e f*), which travels along the line, and ultimately causes the last ball to give a smart stroke against the pad (D).

If you could creep into the tube of the ear you would find, a little way in, a beautiful fine membrane called the tympanum, or tympanic membrane. The shock of the pulses of air falling on this membrane causes it to shiver; its tremors are transmitted to the auditory nerves, and by them are conveyed to the brain and cause you to have the sensation which we call sound.

You ought to be able now to figure the way in which the explosion of this pop-gun is transmitted through the air. I place a ramrod in the tube, there is a cork in the other end, and pushing the rod towards the cork, I cause a crowding together of the particles of air, this they resist, as I can feel by the force I am compelled to exert, and at last their combined resistance takes effect by blowing out the cork at the other end with a sort of explosion.

The suddenly expanding air communicates its motion to the air adjacent to it; this again to the air farther off; finally the condensed pulse strikes the tympanum of your ears, and you hear the noise.

I can show you the passage of a pulse through air in another way. We have here a tube 11 feet long, and about 4 inches wide, its two ends are closed by thin sheet india-rubber. Against the india-rubber surface at one end a cork gently presses (as in Fig. 2, *a*), to the cork a slender stem is attached having a little hammer at its upper end (*b*), kept from striking the bell (*c*), against which it abuts by a slender wire spring (*d*). If now a pulse be sent from the other end of the tube the india-rubber will drive away the cork, and will drive the hammer against the bell. A dull push will not ring the bell at the farther end. The particles of air are very mobile and readily slip round one another, so that it requires a sharp shock to generate a sound wave in the tube and make the bell ring outside the tube. I tap sharply with my fingers on the india-rubber and the sound of my tap and the blow of the hammer upon the bell at the other end of the tube are audible at one and the same time. This tube is 11 feet long, sound travels through air of the temperature of this room at about the rate of 1,100 ft. per second; the time therefore taken by the sound wave in traversing this tube is $\frac{1}{110}$th of a second, an interval of time far too minute to be measured by our ears.

Air is therefore a carrier or transmitter of sound. Suppose we remove the air from about a sounding body, will it then be heard? This experiment was made by Mr. Hawksbee a great many years ago (1705). A bell with a hammer worked by clock-work is placed under a glass globe. From the globe we will pump as much of the air as we can. At present you hear the sound with perfect distinctness, the pumping has at first apparently little effect upon the sound, but very soon it dies away, and now you see the hammer thumping away upon the bell, without producing any noise. It is doing its work in perfect silence. I allow the air to re-enter the glass globe, the tinkling sound of the bell is soon heard, and quickly grows up into the usual musical ring.

We have therefore proved that when the air is removed we have no sound, and when the air returns the sound returns also.

We will now follow the matter up a little further. Prof. Leslie found that when a little air was in the chamber surrounding the bell, and you could hear a little sound, that if the space from which the air had been taken was filled up with hydrogen, that the hydrogen quenched the sound. Now Prof. Stokes has shown us that to create a sound-wave in hydrogen a sharper tap is necessary than in air, so that the shock that produces a sound-wave in air does not suffice to produce a sound-wave in hydrogen (which is a much lighter and less dense gas).

My assistant, Mr. Cottrell, has devised the experiment I am about to show you to demonstrate this effect.

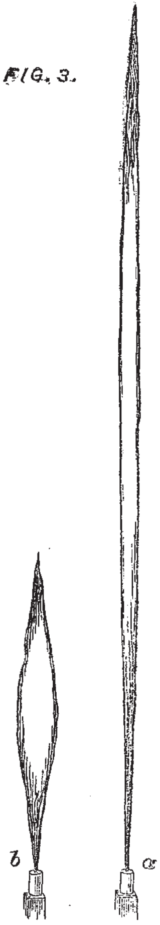
I have a long tin tube (Fig. 2) narrower than the one I used just now, but having like it a piece of india-rubber stretched over each open end, with a hammer and bell arranged against one of them, as before; at the other is a cork hammer fixed to a thin strip of steel, which can be drawn back to any given distance (measured on *f* graduated card). I have thus the means of sending a pulse along the tube as before and making the bell at the other end sound, but I now do it by a stroke of measured force. I now let hydrogen into the tube at the end adjacent to the striking cork (by the tube H), which is a little lower than the other end, and while the hydrogen is entering I continue to send pulses of measured strength along the tube; the bell continues to sound for a little while, but in one minute a sufficient amount of air has been displaced to cause the bell to cease ringing. When we remove the hydrogen you again hear the bell, showing that the pulse can again be carried from end to end of the tube.

Up to this point our illustrations have been audible; I now wish to render visible to you the action of a tube in preventing the dissipation of the sound. The test that I propose to use is a flame. I have behind the table a good-sized gas-holder, by which gas can be forced through a steatite burner. I light it, and we have that long pointed flame (Fig. 3 *a*), and we shall find that that flame is very sensitive. Chirrup to it, and see how rapidly it answers; a great part of the length of the flame is abolished instantly when the sound wave reaches it (Fig. 3 *b* and *c*). I rattle money, tap two keys, and this flame jumps in response to each jingle that I make. The current of air in the room, owing to our care for your comfort in the matter of fresh air, prevents these phenomena showing themselves as well as they do when the theatre is empty; but they are perfectly manifest. No one in this room can hear my watch ticking; but if I hold it near the flame you can distinctly hear the flame give a little roar, and see it suddenly shorten for each tick of the watch. The regularity with which it jumps indicates the regularity with which my watch is ticking.

And now observe the action of a tube in preventing the dissipation of sound. Using a less sensitive flame as the sound-test, I take off the india-rubber ends from our 11-foot tube, and place the flame at the end farthest from myself. The tapping of these two keys together does not affect the flame; but now, my distance from the flame being as great as before, I tap them opposite the open end of the tube, and each tap is rendered, by means of the flame, as visible to your eyes as it is audible to your ears.

Through the unconfined air this small bell does not affect the flame when set ringing; but when I place it at the extremity of the tube the flame dances to each stroke. Speaking-pipes possess their value solely from their preventing the dissipation of

FIG. 3.



the sound pulses; they act precisely as this tube does.

As you know, light cannot well get round a corner; neither can sound, though it does so more easily than light. This little bell acts automatically. I wind it up and start it. At a few feet distance the flame answers to each stroke. Placed behind a board, the flame becomes tranquil. I again bring it out from behind the board, and the flame jumps to each movement of the hammer. (For this experiment the sensitive flame was arranged as in Fig. 4, with a large glass funnel having its tubular end opposite the root of the flame; the board was held about 10 feet distant from the mouth of the funnel.) Sound therefore can be shaded off in the same way that light can be.

In this box, which is well padded, is a bell which I can set ringing at pleasure. The only way by which the sound can get out is this small square opening at one side of it. The bell is now ringing without affecting the sensitive flame (arranged as in Fig. 4); but when this box is turned round, so that its opening faces the quiet flame, we have it dancing and jumping as before.

In other respects also there is a similarity between the mode of action of sound and light.

When a beam from the electric lamp is allowed to fall upon the glass mirror in my hand, it is reflected from the mirror, and the track of the beam being marked by the dust floating in the room, you can see the direction which it takes. This is in accordance with a well-known law, namely, that the angle of incidence is equal to the angle of reflection. It is perfectly plain to you that a line drawn so as to fall at right angles upon this mirror would divide that large angle formed by the two beams of light into two equal angles.

I hope now to make visible to your eyes the reflection of sound in obedience to the same law.

At one corner of the lecture table I place our sensitive flame (*b*), at the opposite corner the padded box containing the electric bell (*a*) with its opening directed in the path taken a moment ago by the beam of light, and I will hold this board (*c*), when everything is ready, where I before held the glass mirror. My assistant will now set the bell ringing. You observe that the flame is uninfluenced by it, but when I bring the board forward, the shortening of the flame at each stroke of the bell, proves that the law of the reflection of sound is the same as the law of the reflection of light: the angle of incidence is equal to the angle of reflection. In this case the flame is knocked down by an echo.

We have thus considered the reflection of sound from a plane surface; let us now see if it behaves like light when reflected from plane surfaces.

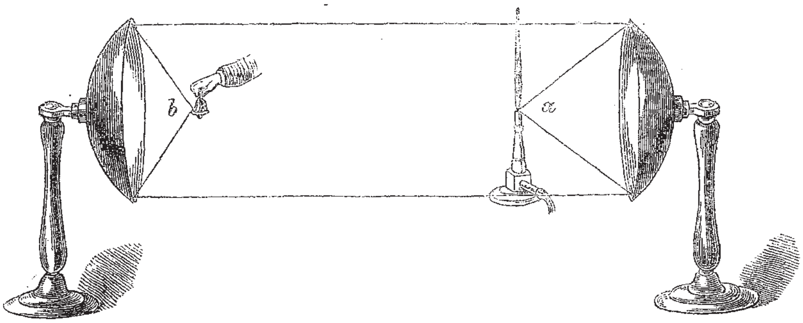


Fig. 6.

The beam of the electric lamp is now directed upon the concave mirror. You can see the band of light marked in the fine dust floating in the air; as soon as it strikes the polished surface it is thrown back, but the rays no longer pursue parallel paths, they are converged, thrown together into one spot. By holding a piece of tracing paper at the point where they meet, termed the focus, the brilliant little star of light caused by their convergence is made visible.

Substitute for the lamp a small bell, and for the tracing paper at the focus of the mirror our sensitive flame, and the conditions are the same as in the previous experiment, sound-waves taking the place of the waves of light. You cannot see the track of these aërial pulses as you could the luminous ones, but their obedience to the same law of reflection is very manifest by the shortening of the sensitive flame as each sound wave reaches it. The flame when out of the focus of the mirror is unaffected; replace it in the spot when the sound waves are crowded together, and it responds to each stroke. Move the bell so that the sound pulses, though only having the same distance to travel to the flame, no longer fall on the mirror: the flame remains perfectly quiet.

We may go further still. Here are a pair of mirrors, the curvature and size of which is the same. They are arranged so as to face one another. A light is placed in the focus of one, that its rays which fall divergent upon the curved surface are reflected from it parallel, they travel to the opposite mirror, and are again converged; a piece of tracing paper held at the focus of the farther mirror shows the spot of light as before (Fig. 6).

Sound is reflected in precisely the same way, and the sensitive flame when carefully manipulated can be used as a means of proving this fact. For these experiments it is essentially necessary that the flame be reduced to the proper pitch of sensitiveness. By reducing the pressure of the gas we can regulate the flame so that it will not respond unless strongly agitated. The flame is placed in the focus of the mirror (*a*), and when the bell is rung, not being in the focus of the conjugate mirror, there is no action. I now bring it into the focus (*b*) and the flame shows a very strong action.

By other modes of experimenting it has long been ascertained that sound was thus reflected from plane and curved surfaces; but never before have these phenomena been made visible. Hitherto these effects have been investigated by the sense of hearing; I have now been able to prove them by appealing to your eyes.

(*To be continued.*)

SCHOLARSHIPS AND EXAMINATIONS FOR NATURAL SCIENCE AT CAMBRIDGE, 1874

THE following is a list of the Scholarships and Exhibitions for proficiency in Natural Science to be offered at the several Colleges in Cambridge during the present year:—

TRINITY COLLEGE.—One or more of the value of about 80*l.* per annum. The examination will commence on